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SOURCES OF TRACKING ERROR IN MILLIMETER WAVELENGTH MISSILE GUID--ETC(U)

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SOURCES OF TRACKING ERROR IN MILLIMETER WAVELENGTH MISSILE GUIDANCE SYSTEMS.

U.S. ARMY
MISSILE
RESEARCH
AND
DEVELOPMENT
COMMAND

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31 May 79

Redstone Arsenal, Alabama 35809

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A number of sources of error degrade the tracking performance of practical millimeter radars. These include receiver noise, target noise, multipath, clutter, servo noise and propagation effects. In this technical note, these error sources are considered, and the available techniques for minimizing their influence are reviewed. A detailed analysis of a typical millimeter radar tracking a military target has been performed in order to evaluate the relative importance of the different sources of tracking error. Both frequency agile and fixed frequency operation are considered.

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PREFACE

The author performed this effort under the sponsorship of the Army Research Office's Scientific Services Program (Contract No. DAAG29-76-D-D100, Delivery order No. 0822). The author is currently a professor of Electrical Engineering at the University of Alabama, Tuscaloosa, Alabama.

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ILLUSTRATIONS

1. INTRODUCTION

The performance of a millimeter wavelength command guidance system is determined primarily by the accuracy with which the millimeter radar can track the missile and the target. The accuracy of a millimeter wave beamrider is also determined by the radar tracking errors, and, while active and semiactive RF terminal homing systems may not employ separate radars, their seekers are subject to the same types of tracking errors. It is important, therefore, that their sources of tracking errors which limit the performance of these systems be identified and carefully evaluated in the context of a millimeter wave missile guidance system.

Among the most important sources of these errors are thermal noise, receiver noise, target noise, multipath, clutter and propagation errors. Although these same error sources are found in radars operating at conventional frequencies, their effects are often found to be both quantitatively and qualitatively different in the millimeter regime. Thermal noise, for example, is frequency dependent, and receiver noise depends upon the quality of the components that are available at a particular frequency. Clutter, multipath and target noise depend on the ratio of the wavelength to the physical dimensions that characterize the roughness of the surface and hence are strongly frequency dependent. Thus theory which has been developed for lower frequency systems may or may not be directly applicable in the millimetric regime.

Another problem in applying existing theory to missile guidance radars is that land combat situations often involve geometries that are not considered in most conventional analyses. For example, most discussions of "low angle" tracking consider antennas and targets that are a few tens to a few hundred meters above the ground, whereas in a typical land combat situation both the antenna and target elevations may be only one or two meters. Such extreme grazing angles will invalidate the assumptions of many analyses.

In this technical note, an attempt is made to survey the various sources of tracking errors and to evaluate their effect on a millimeter wavelength missile guidance system operating in a typical land combat environment. The major goals of this study are: (1) to identify the sources of tracking error which are most important in determining the performance of a millimetric wave system; (2) to suggest ways of improving system performance by reducing or eliminating these error sources; and (3) to identify areas in which additional experimental and/or theoretical investigations are needed to satisfactorily characterize the tracking errors. The major emphasis of this report has been directed toward multipath effects, clutter, and angular target noise (glint) since these are the areas in which a millimeter wavelength system differs significantly from a low frequency radar.

2. RECEIVER NOISE

The tracking error in a millimeter radar due to receiver noise can be evaluated using the well known relation[1]

$$\sigma_T = \frac{1.4\theta_B \sqrt[4]{C_D/C_A}}{k_s \sqrt{B\tau (S/N)(f_R/\beta)}} \tag{1}$$

Where σ_T is the rms tracking, error, θ_B is the beam width, k_s is the error slope, B is the IF bandwidth, τ is the pulse width, S/N is the IF signal to noise ratio, f_r is the pulse repetition frequency, and β is the servo bandwidth. The quantities C_D and C_A are the detection factor and the servo factor. For signal to noise ratios greater than a few dB, the factor (C_D/C_A) may be taken as unity. Equation (1) is appropriate for a conical-scan tracking system; the error in a mono-pulse system would be the same except that the constant 1.4 would become unity.

In applying Equation (1) the signal-to-noise ratio is computed from the radar range equation (1).

$$\frac{S}{N} = \frac{P_T G^2 \lambda^2 \sigma e^{-2\alpha R}}{(4\pi)^3 R^4 kTBN_F L} \tag{2}$$

where P_T is the transmitted power, λ is the wavelength, σ is the radar cross section, α the atmospheric attenuation, R the range to target, k Boltzmann's constant, T the noise temperature, N_F the receiver noise factor, and L the system power losses, G is the antenna gain given by

$$G = \frac{4\pi A\eta}{\lambda^2} \tag{3}$$

where A is the antenna area and η is an antenna efficiency factor. Likewise the antenna beam width can be estimated from

$$\theta_B = 0.885 \frac{\lambda}{D\sqrt{\eta}} \tag{4}$$

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1. D.K. Barton, *Radar System Analysis* Artech House, Dedham, Massachusetts, 1976, p. 279.

The application of Equation (1) to (4) is straight forward and is no different at millimeter wavelength than at other regions of the RF spectrum. The magnitude of some of the quantities involved are somewhat different at millimeter wavelengths however.

A. ANTENNA GAIN (G) AND BEAMWIDTH (θ_B)

Since the beamwidth is proportional to wavelength for constant antenna dimensions, the millimeter waves are capable of obtaining narrower beam with correspondingly greater antenna gains. From Equations (1) to (4) it can be seen that the tracking error is proportional to the wavelength squared. Hence millimeter and submillimeter wavelength systems are inherently more accurate than longer wavelength systems. It should be noted, however, that to obtain the same antenna efficiency at the shorter wavelengths requires that the antenna structures be manufactured with proportionately tighter tolerances.

B. POWER (P_T)

The power available in the millimeter region using current devices is considerably less than at longer wavelengths. Some tubes such as the Extended Interaction Oscillator (EIO) are capable of delivering tens of killowatts in the millimeter region; however, most tactical systems would require a solid state transmitter. At present solid state oscillators in the millimeter region are relatively low power. A typical IMPATT diode can deliver about 1.5 W peak at 95 GHz, 0.75 W at 140 GHz and 0.38 W at 220 GHz. Unfortunately, these devices have very poor coherence properties, and Gunn diodes, which are more coherent, provide only a few tens of milliwatts at these frequencies. Although the output power of presently available solid state devices is marginal, it seems likely that IMPATT diodes capable of delivering 5 to 10 W may be available in the near future and that improvements will be made in the coherence properties of these devices. Guenther and Carruth have done a recent survey of millimeter wave sources.[2]

C. NOISE FIGURE

In general, the noise figures of millimeter wave receivers are considerably poorer than most microwave receivers; typical values are 6.5 dB at 94 GHz., 8.5 dB at 140 GHz, and 13.4 to 16 dB at 230 GHz for uncooled detectors.[3]

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2. B.D. Guenther and R.T. Carruth, *Millimeter Wave Sources for Radar Applications*, US Army Missile Research and Development Command, Redstone Arsenal, Alabama, Technical Report.

3. J. Waldman, *Millimeter and Submillimeter Wave Receivers*, US Army Missile Research and Development Command, Redstone Arsenal, Alabama, Technical Report TE-77-17, 15 July 1977.

D. SYSTEM LOSSES

System losses are much higher at millimetric wave frequencies than at microwave frequencies. Conventional waveguide may have loss as high as 1 dB/foot. Slot guide or quasi-optical techniques may exhibit lower losses.

E. PROPAGATION

Atmospheric attenuation is much greater in the millimeter region that at longer wavelengths. There are atmospheric windows at 95, 140, and 230 GHz; however, as one goes to higher frequencies, each window displays greater clear air attenuation than the previous one. Transmission through dust, smoke and fog is much better than in the optical or infrared regions. Transmission through rain is particularly poor since the drop size is on the order of a wavelength in the millimeter regime.

Typical adverse weather attenuation at 95 GHz would be about 3-4dB/km. This would correspond to fog with 30m visibility or 4 mm/hr. rain. For a more complete discussion of millimeter wave propagation see the report by Gamble and Hodgens.[4]

F. TARGET CROSS SECTION

Some measurements of the radar cross-sections of military targets have been made.[5,6] It is clear that narrower beam widths and higher antenna gains tend to favor the shorter wavelength systems. However, these advantages are offset by the lack of powerful sources, high losses and poor propagation characteristics.

A typical millimeter wave radar might have the following parameters:

Antenna Diameter	D	0.5 m
Antenna Efficiency	η	0.6

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4. W.L. Gamble and T.D. Hodgens, *Propagation of Millimeter and Submillimeter Waves*, US Army Missile Research and Development Command, Technical Report TE-77-14, Redstone Arsenal, Alabama, 22 June 77.

5. D.A. Richer, D.G. Bauerle and J.E. Know, *94 GHz Radar Cross Sections of Vehicles*, Ballistic Research Laboratories Memorandum Report No. 2491, Aberdeen Proving Ground, Maryland, June 1975.

6. *Radar Millimeter Wave Backscatter Measurements and Hard Targets*, Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia, July 1976.

Wavelength	λ	3 mm
Pulse peak power	P_t	1 W
Target Cross Section	σ	20 m^2
Atmospheric Attenuation	α	0.5 dB/km
Range	R	
IF Bandwidth	B	2×10^7
Pulse Width	τ	50 nsec
Noise Factor	N_F	8 dB
Losses	L	13 dB
Error Slope	k_s	1.5
Pulse Repetition Rate	f_r	20 KHz
Servo Bandwidth	β	20 Hz

For such a system the beamwidth θ_B would be 6.8 mrad and the antenna gain 52 dB. The single pulse signal-to-noise ratio would be 3.1 dB and the rms tracking error 0.044 mrad. From this example it is clear that with fairly large antenna and good propagation conditions, the tracking error due to receiver noise can be kept small. For the values used, glint and multipath error will undoubtedly predominate. However, under degraded propagation conditions or at longer ranges, receiver noise could become important.

3. PROPAGATION EFFECTS

There are two types of propagation error. First there is a variation in the refractive index of the atmosphere with altitude. While this effect can cause considerable elevation error in long range search radar, it is clearly unimportant for the relatively short, near horizontal paths being considered here. The second source of propagation error is random fluctuations in the

refractive index due to atmospheric turbulence. These fluctuations can lead to fluctuations in both the apparent angle of arrival and range. The mean square values of these fluctuations can be expressed as follows:[1,7,8]

$$\sigma_R = \sqrt{2\ell_o R\overline{\Delta N^2}} \times 10^{-6} \tag{5}$$

$$\sigma_A = \sqrt{\overline{\Delta N^2} R/\ell_o} \times 2(10^{-6}) \tag{6}$$

where σ_R and σ_A are the rms fluctuations in range and angle of arrival respectively; $\overline{\Delta N}^2$ is the mean square variation of the quantity $N = o(n\text{-}6) \times 10^6$ where n is the refractive index; ℓ_o is a scale factor associated with the turbulence; and R is the range. Both ℓ_o and $\overline{\Delta N}^2$ depend strongly upon the prevaling meteorological conditions. It should be noted that Barton's ℓ_o and $C_n^2 = N\theta/\ell_o$ are not the usual inner scale and structure constant commonly denoted by these symbols. Using the values of $\overline{\Delta N}^2$ and ℓ_o given by Barton we find that for a 5 km range the maximum expected value of σ_A is 2.3×10^{-4} rad and a maximum value of σ_R is approximately 10 cm. Clearly the range fluctuation is insignificant and the angle of arrival fluctuation is small compared to other sources of angle noise.

Equations (5) and (6) are commonly used to estimate the angle and range fluctuations in the microwave region where the wavelength is large compared to the inner scale of turbulence. For the frequencies of interest in this study the wavelength is only 2 or 3 times larger than the inner scale (which is typically is on the order of 1 mm). Therefore, these equations may not be strictly applicable in the millimeter regime. Other expressions for angle of arrival fluctuations have been derived for optical frequencies when the wavelength is much less than the inner scale. Fante gives the following expression:

$$\sigma_A^2 = \frac{2.19 C_N^2 L}{D^{1/3}} \tag{7}$$

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7. R.B. Muchmore, and A.D. Whellon, "Line of Sight Propragation Phenomena II Ray Treatment", *Proceedings IRE* Vol. 43, 1955, pp. 1437-49.

8. A.D. Whellon, "Near Field Correction to Line of Sight Propagation," *Proceedings IRE* Vol. 43, 1955, pp. 1459-1466.

where D is the receiving aperture diameter.[9] Assuming D to be 10 cm, Equation (7) gives a value of 1.5×10^{-4} rad for σ_A which is in reasonable agreement with the results obtained from Equation (6).

Although the agreement between the results of Equations (6) and (7) tends to increase our confidence in the statement that the propagation errors are small for these ranges, it still does not preclude the possibility of larger fluctuations being observed when the wavelength and inner scale are approximately equal. There has been no known theory developed that has been validated for millimeter wavelengths nor have any experimental data at these frequencies been found.

4. MULTIPATH

A. THE MULTIPATH EFFECT

Whenever a radar, or a radar target, is located near the surface of the earth there will be inevitable reflections which will modify the radar antenna pattern causing false targets or, more likely angular errors in the radar tracking. In extreme cases the radar may even track on the reflection of the target in the earth's surface rather than on the target itself.

To understand the multipath phenomenon consider a radar antenna located at "A" and a target at "T", (*Figure 1*). To be specific, it can be assumed that the radar is an amplitude comparison monopulse, although essentially the same result would be obtained by considering a phase comparison monopulse or conical scan radar. In the absence of a multipath signal the apparent angle to the target measured from the antenna boresight is

$$\theta = F \left\{ \frac{|A-B|}{|A+B|} \right\} \tag{8}$$

where A and B respresent the signal in channel A and B, respectively. Since these signals are proportional to the antenna gain in the direction of the target we may rewrite Equation (8) as

$$\theta = F \left\{ \frac{|G_A - G_B|}{|G_A + G_B|} \right\} \tag{9}$$

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9. Ronald L. Fante,"Electromagnetic Beam Propagation in Turbulent Medic," *Proceedings of the Institute of Electrical and Electronics Engineers*, Vol. 62, 1974, pp. 1669-1692.

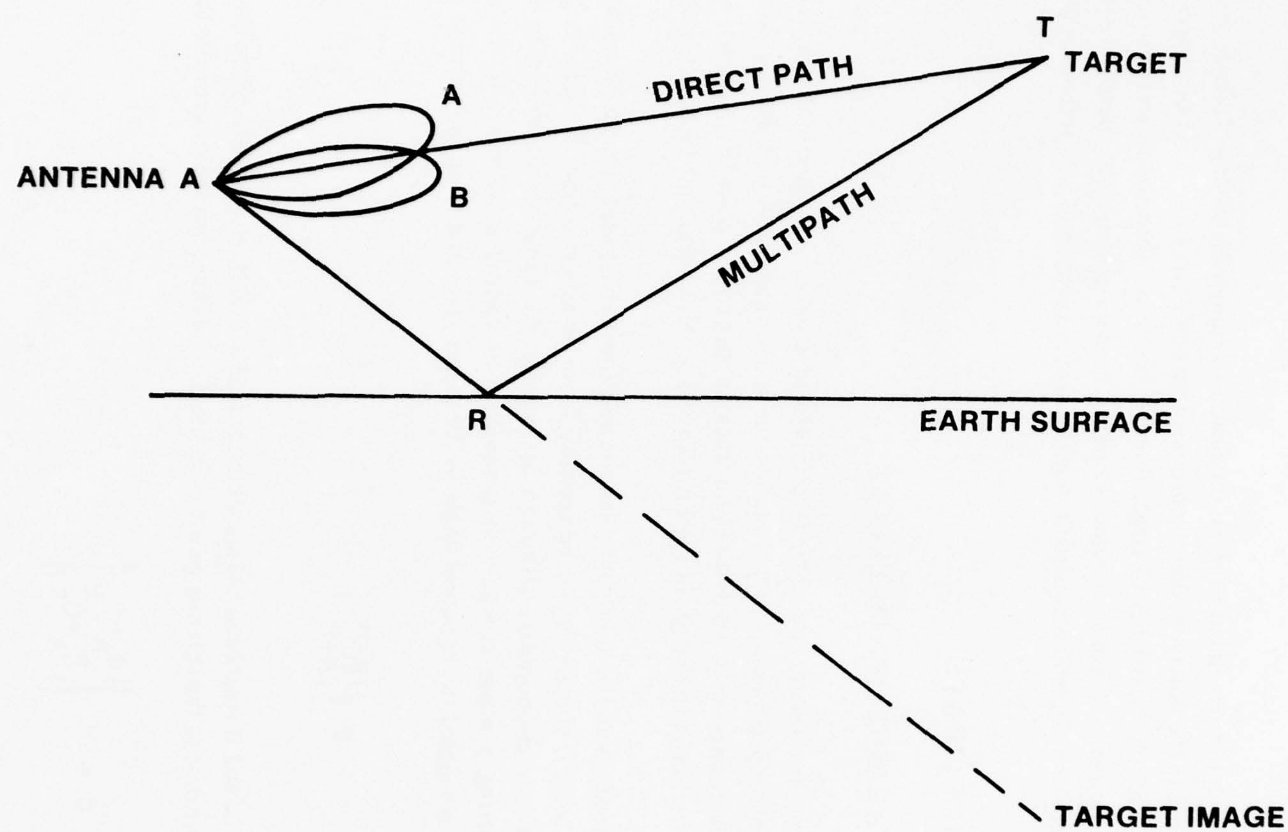

Figure 1. Geometry for specular reflection multipath.

Here G_A and G_B represent the antenna gain of the A and B channels in the direction $\overline{AT}$. Now in the presence of multipath a signal is not only received directly from T but also a second signal reflected by the surface of the earth. This signal will be proportional to G'_A and G'_B where G' denotes the antenna gain in the direction $\overline{AR}$. Now the apparent target direction becomes

$$\theta' = F \left\{ \frac{|(G_A + G'_A) - (G_B + G'_B)|}{|(G_A + G'_A) + (G_B + G'_B)|} \right\} \tag{10}$$

Multipath will then cause an error $(\theta' - \theta)$ in the elevation angle.

The multipath signal may add to or cancel the direct signal depending upon the path length difference in the direct and multipath channels. The multipath error may, therefore, have either sense. In fact, it is well know that in the presence of specular multipath the elevation angle error will oscillate with increasing deviation as the range increases at constant target elevation.

The magnitude of the multipath error depends upon the strength of the reflected signal. This in turn depends upon the antenna gain in the direction of the image and the reflectivity of the surface. If the angle to the target image is large compared to the beam width then the multipath will be small. In fact the one sure way of eliminating multipath is to make certain that the radar main beam never strikes the ground. Likewise if the reflectivity is small the multipath effect will be small. The reflectivity is usually taken as [10]

$$\rho = \rho_o \exp \left[-\left(\frac{4\pi\sigma_h \sin\psi}{\lambda} \right)^2 \right] \tag{11}$$

where ρ_o is the specular reflectivity (usually in the range 0.1 to 0.3 for radar wavelengths), ψ is the grazing angle, ψ the wavelength, and σ_h the rms surface roughness. From this equation it is clear that the reflectivity increases with decreasing angle and decreases with increasing surface roughness.

In addition to specular reflections, there may also be diffuse reflections from the earth's surface. Whereas the specular reflection appears to come from a distinct point, the diffuse

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10. David K. Barton, "Low Angle Tracking," *Proceedings of the Institute of Electrical and Electronics Engineers*, Vol. 62, 1974, pp. 687-704.

reflection will appear to originate over an extended area, the so-called glistening surface.[11] In terms of effect on tracking, the diffuse multipath, being incoherent, will always cause the apparent target position to be depressed. This is in contrast to the effect of the specular multipath which can cause an elevation error of either sense.

B. THEORETICAL ANALYSIS

A considerable amount of both experimental research and theoretical analysis has been devoted to multipath effects. A recent collection of papers summarizes most of the published results.[12] Unfortunately most of the published results are concerned with microwave frequencies and conventional radar geometries. A number of assumptions of these analyses may not be valid at millimeter wavelengths and/or for the geometries that will be encountered by a radar used to guide a ground based ATGM. In particular the following differences in the millimeter wave ATGM guidance problem and a typical tracking radar should be noted.

At millimeter wave frequencies the surface roughness is at least equal to the wavelength and probably will be orders of magnitude greater. It is not clear that the usual treatment of surface reflections is valid for extremely rough surfaces.

The typical "low angle tracking" analysis considers targets tens or hundreds of meters above the reflecting surface. In a typical land combat situation both the radar antenna and the target may be only a meter or two high and may be separated by several kilometers. Thus the grazing angles are much smaller than those usually considered. At these extremely small grazing angles the reflectivity may deviate from the assumed values. Shadowing, which is often neglected, also becomes important.

Another effect of small grazing angles concerns the finite size of the radar antenna and/or the target. For a finite antenna (or target) the multipath is not a single ray but consists of a bundle of rays from each point on the target to each point in the receiver aperture. Therefore, the multipath is not reflected at a single point but over an area on the ground. As the grazing angle becomes small the reflecting area becomes large. In fact, at very small grazing angles this area becomes essentially the entire region between the antenna and the target. The path length from the target to the antenna will depend on where the reflection occurs within this area. For any realistic surface the variations in path length for energy reflected from different points will

11. P. Beckmann and A. Spizzichino, *The Scattering of EM Waves from Rough Surfaces*, Pergamon Press, New York, New York, 1963.

12. David K. Barton, ed., *Radars, Volume 4: Radar Resolution and Multipaths*, Artech House, Dedham, Massachusetts, 1975.

be many wavelengths. Thus the multipath signal will be incoherent even in the case of specular reflections. This will not only reduce the magnitude of the multipath but may also destroy characteristic cyclical behavior of specular multipath error.

Only a few workers have considered the multipath problem specifically at millimeter wavelengths and in general their treatments are not very satisfactory.[13-18] Dees and Schuchardt assume specular reflection leading to a cyclic error which is probably incorrect at millimeter wavelengths.[13] These authors also neglect shadowing. Thompson and Killredge assume an unrealistic (for purposes of this report) antenna size. Shackleford and Gallagher adopt a very simple approach which, while not rigorous, may still give reasonable estimates of the multipath error.[17] These authors simply assume centroid tracking on the center of intensity of the target and its image, the latter being weighted by the surface reflectivity computed from Equation (11). Clearly this approach assumes incoherent addition of the direct and multipath channels even though a specular reflection is assumed. Their approximate expression for multipath error is

$$\sigma_m = \frac{\theta}{3} \frac{\rho}{1+\rho} \tag{12}$$

where it is assumed that the squint angle has been selected to maximize the tracker performance.

Apparently, no analysis of multipath at millimeter wavelengths has considered shadowing nor have any geometries other a plane surface been treated. Also, it has been suggested that for extended targets, glint and multipath are closely interrelated. If this is indeed the case, then an adequate theory of multipath should include the effects of glint.

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13. Julian W. Dees and James M. Schuchardt, *Effects of Multipath on Millimeter Beamrider Systems*, US Army Missile Research and Development Command , Redstone Arsenal, Alabama, February 1978.

14. Victor W. Richard, *Low Angle Tracking at Millimeter Wavelengths*, US Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland.

15. General Research Corporation, *Proceedings of Defense Advanced Research Projects Agency*, Santa Barbara, California, January 1977.

16. Samuel O. Dunlap, *Selected Topics on Radar Multipath*, US Army Missile Research and Development Command, Redstone Arsenal, Alabama, November 1975.

17. R.G. Shackleford, and J.J. Gallagher, *Millimeter Wave Beamrider*, US Army Missile Research and Development Command, Redstone Arsenal, Alabama, Technical Report TR-CR-77-7, August 1977.

18. F.H. Thompson, and F.A. Kittredge, *A Study of the Feasibility of Using 35 GHz and 94 GHz as a Means of Improved Low Angle Tracking*, National Research Laboratory Report 2249, May 1971, Advanced Development 725108.

C. EXPERIMENTAL DATA

There is very little experimental data on multipath effects at millimeter wavelengths. A recent test of a millimeter tracking system indicated that the average error in elevation was no greater than the azimuthal tracking error.[19] Although inconclusive, this tends to indicate that, at least for the terrain used, a relatively flat, grass-covered field in these tests, the multipath error is small compared to receiver noise and glint. Additional experimental studies have been conducted at the US Army Ballistic Research Laboratory[20-30]. In general these results indicate that the multipath error is typically less than one-tenth of a beam width. It is understood that BRL has conducted additional tests of millimeter wave multipath before and after mowing the range.[31] These results are as yet unpublished.

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19. PRIVATE COMMUNICATION

20. Richard V. Victor, *Millimeter Wave Radar Applicaion to Weapon System*, US Army Ballistic Research Laboratory Memorandum Report No. 2631, Aberdeen Maryland, June 1976.

21. K.A. Richer, *4.4 MM Wavelength Near Earth Propagation Measurements* (U), Ballistic Research Laboratories Memorandum Report No. 1403, Advanced Development 331098, May 1962 (Confidential).

22. C.L. Wilson, *Antenna Pointing Errors in Simultaneous Lobing Antenna System*, Ballistic Research Laboratories Technical Note No. 1463, Advanced Development 608997, May 1962.

23. C.L. Wilson, *Antenna Pointing Errors in Sequential Lobing Antenna System*, Ballistic Research Laboratories Technical Note No. 1463, Advanced Development 609009, May 1962.

24. T.W. O'Dell, *Final Report for Missile Guidance Subsystem Feasibility Program - Phase 2* (U), General Precision Laboratories Report No. P026 (Confidential).

25. T.W. O'Dell, *Final Report for Missile Guidance Subsystem Feasibility Program - Phase 2* (U), General Precision Laboratories Report No. 14990, June 1962, (Confidential)

26. N. Leggett, *Final Report, Breadboard Feasibility Study of the Derring Weapon Guidance System*, Bendix Pacific Division Report No. 91-139-1 (U), May 1963.

27. J.E. Kammerer and K.A. Richer, *4.4 MM Near Earth Antenna Multipath Pointing Errors* (U), Ballistic Research Laboratories Memorandum Report No. 1559,Advanced Development 443211, March 1964 (Confidential).

28. J.E. Kammerer and K.A. Richer, *4.4 MM Wavelength Precision Antennas and Mount*, Ballistic Research Laboratories Memorandum Report No. 2730, Advanced Development 484693, January 1966.

29. J.E. Kammerer and K.A. Richer, *140 GHz Millimetric Bistatic Continuous Wave Measurements Radar*, Ballistic Research Laboratories Memorandum Report No. 2730, Advanced Development 484693, January 1966.

30. J.E. Kammerer and K.A. Richer, *Pointing Errors of a 140 GHz Bistatic Radar System Illuminating US Army Targets* (U), Ballistic Research Laboratories Memorandum Report No. 1755, Advanced Development 375942, June 1972 (Confidential).

31. PRIVATE COMMUNICATION.

D. MULTIPATH REDUCTION

A considerable amount of effort has been devoted to developing techniques for eliminating or reducing multipath. In this section the various techniques which have been described in the radar literature will be reviewed, and their application to millimeter guidance will be discussed.

The surest way of eliminating multipath is to exclude the earth's surface from the radar beam. The most straight forward way of making sure that the beam does not strike the surface is to reduce the beam divergence as much as possible. This in turn can be accomplished by using the highest frequency possible, by using the highest frequency possible, by using a large diameter antenna and by a high antenna efficiency. The choice of operating frequency will clearly involve a design trade-off between the reduction of the beamwidth by use of higher frequencies on one hand and reduced available power and increased atmospheric attenuation on the other. The antenna size will be limited by practical consideration and the antenna efficiency by manufacturing tolerances. Since it is desirable to use as small a beamwidth as possible for precision tracking, reduction of multipath by beamwidth reduction puts no new requirement on the system. Even if the radar beam is made small enough to prevent the main beam from striking the earth's surface, it is still possible for multipath returns to enter the antenna through a sidelobe. The antenna should, therefore, be designed for maximum sidelobe suppression.

A second means of preventing the radar beam from striking a reflecting surface is off-axis tracking.[32] In this technique the axis of a monopulse radar or scan axis of a conscan radar is deliberately pointed above the target and tracking is performed with a fixed bias in elevation. Clearly this will reduce the intensity of the beam striking the ground and hence reduce main lobe multipath. Off-axis tracking could have an additional advantage in a differential guidance or beamrider system since it would allow the missile to fly a trajectory above line-of-sight. Because of the very low target height, off-axis tracking will not be able to completely eliminate multipath, but it should be helpful in reducing it somewhat. Off-axis tracking should be easy to implement. The main disadvantage is the reduced antenna gain when working off-axis. Unless the multipath error is large, the gain in tracking accuracy obtained by eliminating multipath may not offset the loss of signal-to-noise due to reduced antenna gain.

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32. W.H. Bockmiller and P.R. Dax, *Radar Low Angle Tracking Study*, National Aeronautics and Space Administration Contract Report No. 1387, Westinghouse Electric Corporation, Baltimore Maryland, June 1969.

Other ways of reducing the multipath return include range gating and velocity gating. It can easily be shown that for a plane earth the direct and multipath ranges are

$$R_D = \sqrt{(h_T - h_R)^2 + R^2} \approx R\left[1 + \frac{1}{2}\frac{(h_T - h_R)^2}{R^2}\right] \tag{13}$$

$$R_m = \sqrt{(h_T + h_R)^2 + R^2} \approx R\left[1 + \frac{1}{2}\frac{(h_T + h_A)^2}{R^2}\right] \tag{14}$$

where h_T and h_R are the target and radar elevations and R is the "over the ground" range. The path length difference is then

$$\Delta R = R_m - R_D \approx \frac{2h_T h_R}{R} \tag{15}$$

and for a target moving parallel to the surface the velocity difference is given by

$$\Delta V = \frac{2R_m}{2t} - \frac{2R_D}{2t} \approx \frac{2h_T h_R}{R^2}\frac{dR}{dt} \tag{16}$$

where dR/dt is the radial velocity of the target. From Equation (15) it is seen that for elevation on the order of meters and ranges on the order of kilometers that the path length difference will be on the order of millimeters. Likewise, the velocity difference will be some five orders of magnitude less than the radical velocity of the target. It is clear that neither range nor velocity gating can distinguish between the direct and multipath returns.

It has also been suggested that polarization could be used as a basis for discriminating against the multipath return. In principle the reflection from a surface should be independent of polarization at grazing incidence. There is, however, some experimental evidence to suggest that even at low angles the reflection from most terrain may be somewhat polarization dependent. This has led to several schemes for using depolarization of the multipath return as a means of rejecting it. Root and Cullis, for example, have proposed a technique which they call polarization processing where consecutive pulses are transmitted with alternately horizontal and vertical polarization.[33] Horizontally polarized pulses are also shifted 90° in

33. Lloyd W. Root, and R.N. Cullis, *Multipath Environment Active RF Seeker (MARFS)*, US Army Missile Command Report.

phase with respect to the vertically polarized pulses. The return signal is separated into horizontal and vertical polarizaions and the phase difference in the two channels compared. If there is no depolarization, this will be either +90° or -90°, depending upon whether the signal is an odd or even bounce return. With depolarization a distribution of phases will be observed. For multipath reduction Root and Cullis suggest using the returns near +90° and -90°. The stronger signal would be assumed to be due to multipath.

The multipath could be reduced by minimizing the surface reflectivity. This would be done by choosing a wavelength at which the surface absorption is large, by using a high frequency to make the surface roughness large compared to the wavelength or by a proper choice of polarization.

In fixed radar installations passive screening is frequently used to reduce both multipath and clutter. However, this is clearly impossible for a tactical missile guidance system.

Another technique for reducing multipath is to change the frequency of the transmitted signal sufficiently to cause the multipath error to go through a complete cycle, thus averaging out the error. The frequency could be varied on a pulse to pulse basis or could be swept during each pulse. In either case the requirement is that the phase difference between the direct and multipath returns be varied by at least 2π rad during the measurement period. The Ballistics Research Laboratory has experimented with this technique and claims that the results indicate that wideband frequency diversity appears promising not only for multipath reduction but also for reducing target noise and background clutter.[34] The principal difficulty that we see in the use of frequency agility in ground-to-ground situations is that the small path length differences involved will necessitate an excessively large bandwidth. From Equation (15) it follows that

$$d(\Delta\phi) = \frac{4\pi h^2}{\lambda R}\left(\frac{df}{f}\right) \tag{17}$$

where $\Delta\phi$ is the difference in phase between the direct and multipath channels and $d(\Delta\phi)$ is the change in this difference for a frequency change Δf. From Equation (17) it is clear that for h (the geometric mean of h_T and h_R), less than a few meters, an excessive frequency change will be needed to produce the desired 2π rad change in phase.

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34. R. McGee, *Multipath Suppression by Swept Frequency Methods*, Ballistic Research Laboratories Memorandum Report No. 1950, Advanced Development 682728, November 1968.

All of the methods for reducing the multipath error discussed so far have attempted to minimize or eliminate the reflected signal or to resolve the target and its image. A second class of techniques accepts the multipath return as inevitable and treats the image as a second unresolved target. These techniques generally employ monopulse radars with more elaborate beam patterns, symmetrical error patterns and asymmetrical monopulse, use additional information about the target contained in the quadrature component of the radar return complex angle techniques or use statistical estimation theory multiple target estimation. We will not attempt to describe these techniques in detail since there are many variations of each and since they have all been extensively described in the literature.[12] Each of these techniques has been carefully reviewed for applicability to a millimeter wave guidance of a light, ground based ATGM. It is estimated that these techniques are generally difficult to implement and offer only slight reduction in multipath. In addition, many of them have serious limitations which make them unsuitable for this application. Complex angle techniques, for example, are subject to serious ambiguities and also require calibration at a specific site. Considering the problems with these techniques, it is not believed that any of them will prove to be useful for millimeter wave missile guidance systems.

5. TARGET NOISE

Target noise refers to fluctuations in the radar return due to characteristics of the target. These fluctuations are primarily of two kinds; i.e., amplitude noise or scintillation and angle noise or glint. There are other types of target noise such as range noise, Doppler noise, etc., but these will not be considered here.

Both amplitude and angle noise depend upon the power spectrum of the fluctuations introduced into the radar return by target motion. This spectral density $\omega(h)$ is usually taken to be a triangular function with maximum ω_0 at zero frequency and a cut-off frequency f_g given by

$$f_g = \frac{2\omega_g L}{\lambda} \tag{18}$$

where ω_g is the rate of change of target aspect and L is a length characteristic of the largest target dimension. Alternately ω may be taken to be a Markoffian Spectra

$$\omega = \omega_o \frac{f_g^2}{f_g^2 + f^2} \tag{19}$$

The tracking error due to amplitude noise can be computed in a manner similar to that used to find the error due to thermal noise, i.e., by equating the modulation required to produce a given amount of power in the servo channel to the power introduced by the noise. For a conical scan system this is given by

$$\sigma_s = 0.67\theta_B \sqrt{w(fs)\beta_s} \tag{20}$$

where f_s is the scan frequency and β_s the servo bandwidth. Barton has shown that for $f_s >> f_g$ and for a Rayleigh target Equation (20) reduces to

$$\sigma_s = \frac{0.27\theta_B}{fs} \sqrt{fg\theta_B} \tag{21}$$

using the values for β_s amd θ assumed in Section 2 and assuming $f_s =$ 100 Hz and $f_g = 5$ Hz. This value of 5Hz for f_g is close to the value computed from (18) for a 3m long target crossing at 30 km/hr at a range of 3km and a wavelength of 3mm. Most large amplitude vehicle vibrations are also at frequencies in the range of a few tenths Hz to a few Hz. Thus 5Hz seem as to be a reasonable maximum value for f_g for land targets. We find that σ_s is less than 0.02 mrad, which will be generally negligable compared to other error sources.[1]

Angle noise or glint is associated with fluctuations in the apparent angle of arrival of the reflected wave at the receiving antenna. These fluctuations arise from interference between waves reflected from different parts of the target. As the target range or aspect changes, the way in which the waves interfere varies, causing the apparent target centroid to wander randomly. The maximum excursions can be extremely large; in fact, for two point sources the glint error can be 90° for certain amplitude and phase relations between the individual returns. A real radar will not track this extreme fluctuation due to practical limitations such as finite antenna size and limited servo bandwidths. However, it is possible for the apparent target centroid to lie outside the physical target.

Estimation of the tracking error due to glint involves assumption about the distribution of the individual scatters which contribute to the radar return. In an early paper Delano considered a collection of scattering centers with random phase and various spatial

distributions.[35] Delano gives the root mean square fluctuation of the effective radar center about its mean position as

$$\sigma_g = \frac{L}{\sqrt{2\pi}R} \tag{22}$$

for scattering centers located in two groups at the ends of a target of length L and the value of

$$\sigma_g = \frac{L}{\sqrt{6\pi}R} \tag{23}$$

for the scatters uniformly spaced along L. A common practice is to assume that the glint error is Gaussianly distributed with an rms value

$$\sigma_g = 0.35 \frac{L}{R} \tag{24}$$

which would be characteristic of a non-uniform distribution of the scattering centers along L. It should be noted that Equation (24) implies that the apparent radar center will be outside the target approximately 10% of the time. As a numerical example, consider a 3m target at a range of 3 km. The glint error would be 0.35 mrad and would increase with decreasing range.

The applicability of Equation (24) clearly depends upon how well the actual target resembles a random array of more or less equally strong scattering centers. It has been suggested that a typical vehicle does not resemble this ideal distribution of scatters but consists of a relatively small number of "hot-spots" or "sub-targets" that are strongly reflecting. These sub-targets themselves might consist of a collection of random scatters. If this were the case, then Equation (24) would be applicable to each sub-target (with L being a dimension characteristic of the "hot spot") rather than being applicable to the vehicle as a whole. The sub-targets referred to might be a wheel, a plate oriented in the proper direction or the corner between two plates that act as a corner reflector, etc.

The usual model Equation (24) and the sub target model are expected to lead to quite different tracking behavior. In the former case the glint error will lead to a uniform, wander of the tracking spot over and occasionally off the target. In the later case the glint error will be

35. Richard H. Delano, "*A Theory of Target Glint or Angular Scintillation in Radar Tracking,*" *Proceedings IRE*, Vol. 41 1953, p. 1778.

small most of the time, since L is small, but will have an occasional large excursion as the tracker loses lock on one sub-target and jumps to another. Available tracking data tends to indicate that small tracking errors with occasional large excursions are in fact observed at millimeter wavelengths, lending credibility to the sub-target concept.[19]

Very little work has been done toward modeling military targets at millimeter wavelengths. Attempts have been made to describe a tank in terms of the radar cross section as simple shapes that could be related to the vehicle's features.[36] Unfortunately, this has yet to produce a model of much practical value. Nor has a statistical model for a collection of sub-targets been developed. Clearly more work is needed in the area of target modeling.

There are a number of ways in which the glint error can be reduced. One of the most widely accepted ways is by means of frequency agility or diversity.[37] Here the frequency is changed either by FM modulation of the pulse or by changing the frequency from pulse to pulse. Changing the frequency changes the phase relation between the waves reflected from individual scatters causing a rapid fluctuation in the position of the radar centroid. If the fluctuation is large and occurs in a time that is short compared to the time required to make a measurement of angle, then the glint effects will be averaged. It can be shown that the frequency change necessary to reduce the glint corrolation function by one-half is:

$$\Delta f \approx \frac{45}{D'} \text{ (MHz)} \tag{25}$$

where D′ is the depth of the target in meters.[38] To significantly reduce glint the pulse to pulse frequency shift must be large compared to this value. Unfortunately, for a tank target most of the reflection may come from the surfaces nearest the radar. Thus the value of D′ will not be the actual depth but the depth over which significant radar reflection occurs. In a direct frontal or side-on aspect this distance may be small, hence the required frequency agility may be larger than anticipated.

Lind gives a more precise method of estimating the glint reduction for a given frequency agility.[39] We assume that the frequency is varied on a pulse to pulse basis and that the

36. A.W. Straiton, *Radar Target Modeling at 94, and 220 GHz*, Final Report on Contract DAAG29-76-D-0100. US Army Missile Research and Development Command, Redstone Arsenal, Alabama, January 1978.

37. David K. Barton, ed., *Radars, Vol. 6: Frequency Agility and Diversity*, Artech House, Dedham, Massachusetts 1977.

38. Ray Howard, "Improving Radar Range and Angle Detection with Frequency Agility," *Microwave Journal*, May 1966, p. 63.

39. Goran Lind, "Reduction of Radar Tracking Errors with Frequency Agility," *Institute of Electrical and Electronics Engineers Transactions Aerospace and Electronic System*, AES-4, 1967, p. 410.

individual pulse frequencies are uniformly distributed over the frequency range Δf_{max}. Then the total glint power is

$$\eta^2 = L/6\pi \tag{26}$$

and the zero frequency glint spectral density of a fixed frequency radar is given by

$$\omega_o = \eta^2/fg \tag{27}$$

where f_g is the characteristic glint frequency from Equation (18).

Now the decorrolation function for the glint is written:

$$\rho_c = 2\frac{\Delta f_c}{\Delta fmax} \tag{28}$$

where

$$\Delta f_c = \frac{c}{2D} \tag{29}$$

Now the zero frequency spectral density for the frequency agile radar is

$$\omega = (1-\rho_c)\ \frac{\eta^2}{fr/2} + \rho_c\omega_o \tag{30}$$

and the effective number of independent samples is given by

$$N = \frac{\omega o}{\omega} \tag{31}$$

Consider a tank 6 m long crossing at a range of 3 km with a speed of 36 km/s being tracked by a 94 GHz radar, then

$$\omega = \frac{(36\ kM/Hr)/(3600\ sec/Hr)}{3\ Km} \cong 0.003\ rad/sec$$

and

$$fg = \frac{26\omega}{\lambda} = 12\ Hz$$

If the effection value of D as 1.5 m is taken, then $\Delta f_c = 10^8$ Hz. If $\Delta f_{max} = 10^9$ Hz is assumed, then $\rho_c = 0.2$. With a prf of 20 khz

$$\omega_o = 0.158 \ m^2 Hz^{-1}$$

and

$$\omega = 3.16 \times 10^{-2} \ m^2 Hz^{-1}$$

Hence for the high prf being considered, the approximation:

$$N \simeq 1/p_c$$

may be used.

For the example given, $N = 5$.

Finally, the glint error for the frequency agile radar may be expressed as

$$\sigma_g \text{ (agile)} = \sigma_g \text{ (fixed freq.)}/\sqrt{N}$$

Therefore in the preceeding example the error would be reduced by a factor of about 2.2.

From the example calculation it is seen that frequency agility should be able to significantly reduce the glint if the target reflections arise at appreciably different ranges. This would be the case if the target were crossing at an angle. In a direct frontal or side-on aspect most of the radar return might come from a single plane of nearly constant range. In this case the apparent depth of the target will be so small that the effectiveness of the frequency diversity is significantly reduced.

A second way of reducing glint would be to increase the range resolution to a point that only one sub-target would be in the range gate. The rms glint would then be small because of the small dimension of the sub-target, and leaps from one sub-target to another would be eliminated. This technique has some problems, however. First, by discriminating against part of the target one is reducing the reflected power and, hence, the signal-to-noise ratio. This may not be as serious as it seems, however, since when the system is tracking on one hot spot, the return from the remainder of the target may be treated more like clutter than signal. A second difficulty is the very narrow pulses required. To be effective, this technique sould require range resclutions on the order of tens of centimeters which implies nanosecond or sub-nanosecond

pulses. Finally, tracking on one hot-spot may lead to guiding the munition to a point near one edge of the target. With the addition of other noise sources, this could lead to missing the target or to hitting the target at a point that offers very little chance of a kill. Clearly, then, there must be a trade between tracking a point near the center of the target with relatively large rms error and occasional leaps and tracking with greater precision on a point that could be near the edge of the target. The resolution of this question requires consideration of target vulnerability, missile guidance characteristics, lethality and other factors.

6. CLUTTER

Random reflections from the surface of the earth (ground clutter), from particles in the atmosphere (weather clutter) or from material intentionally deployed to defeat the radar (chaff clutter) will tend to degrade the tracking performance of a radar. In this section the effect of ground clutter on a millimeter wave radar is considered.

In order to estimate the ground clutter from a flat surface, an effective clutter cross-section σ_c given by

$$\sigma_c = \sigma_o A_c \tag{32}$$

is considered where A_c is the *reflecting surface area and* σ_o is a constant which depends upon frequency, incidence angle and the nature of the terrain. For low depression angles A_c may be expressed by

$$A_c = \frac{\theta_B R}{\sqrt{2}} \frac{c\tau}{2} \frac{1}{\cos\delta} \tag{33}$$

where δ is the depression angle and the other quantities have been previously defined. The beam divergence is given by

$$\theta_B = \sqrt{\frac{2}{\pi}} \frac{1}{\sqrt{\eta}} \frac{\lambda}{D} \tag{34}$$

The relative clutter cross section σ_o can be estimated for any frequency and incidence angle from the relation

$$\sigma_o = -C_1 + C_2 \log\left(\frac{\theta_s}{\theta_o}\right) - C_3 \log\left(\frac{\lambda}{\bar{\lambda}}\right) \tag{35}$$

where θ_s is the grazing angle, λ is the wavelength, and C_1, C_2, C_3, θ_o and λ_o are empirical constants which depend on the terrain. Values for these constants are given in *Table 1*. The relative clutter cross section computed from Equation (35) for a frequency of 95 GHz is shown in *Figure 2* (solid curves).

There have been few good measurements of clutter at millimeter wavelengths.[5,6,40-46] The measured values of σ_o vary considerably due to differences in terrain. For this reason no attempt has been made to plot the measured data, but the range of measured values of σ_o has been indicated on *Figure 2* (cross hatched areas). It can be seen that for 95 GHz the value of σ_o estimated from Equation (35) agrees reasonably well with the experiment.

TABLE 1. CONSTANTS FOR USE IN ESTIMATING RELATIVE CLUTTER CROSS-SECTION FOR VARIOUS TERRAIN

C_1 dB	C_2 dB	C_3 dB	θ_o (Deg.)	λ_o (Cm)	TERRAIN
16	26	8	35	1.0	Crops
20	26	10	35	1.5	Grass
31	18	15	25	1.5	Loam
28	18	15	25	1.5	Gravel
25	25	15	30	1.5	Snow
39	32	20	25	2.2	Concrete
11	26	8	35	1.0	Trees
6	5	3	30	1.0	Urban

40. George M. Green, Welsey H. Shaw and James P. Stewart, *Target Background Measurements Using Pulsed Millimeter Wave Seeker*, Martin Marietta Aerospace Corporation, Orlando, Florida, 19 November 1975.

41. R.S. Roeder, et. al., *Millimeter Wave Semiactive Guidance System Concept Investigation*, Sperry Microwave Electronics Division Report No. SJ242-847A-5, Final Report, Defense Advanced Research Projects Agency Order No. 3146, November 1978.

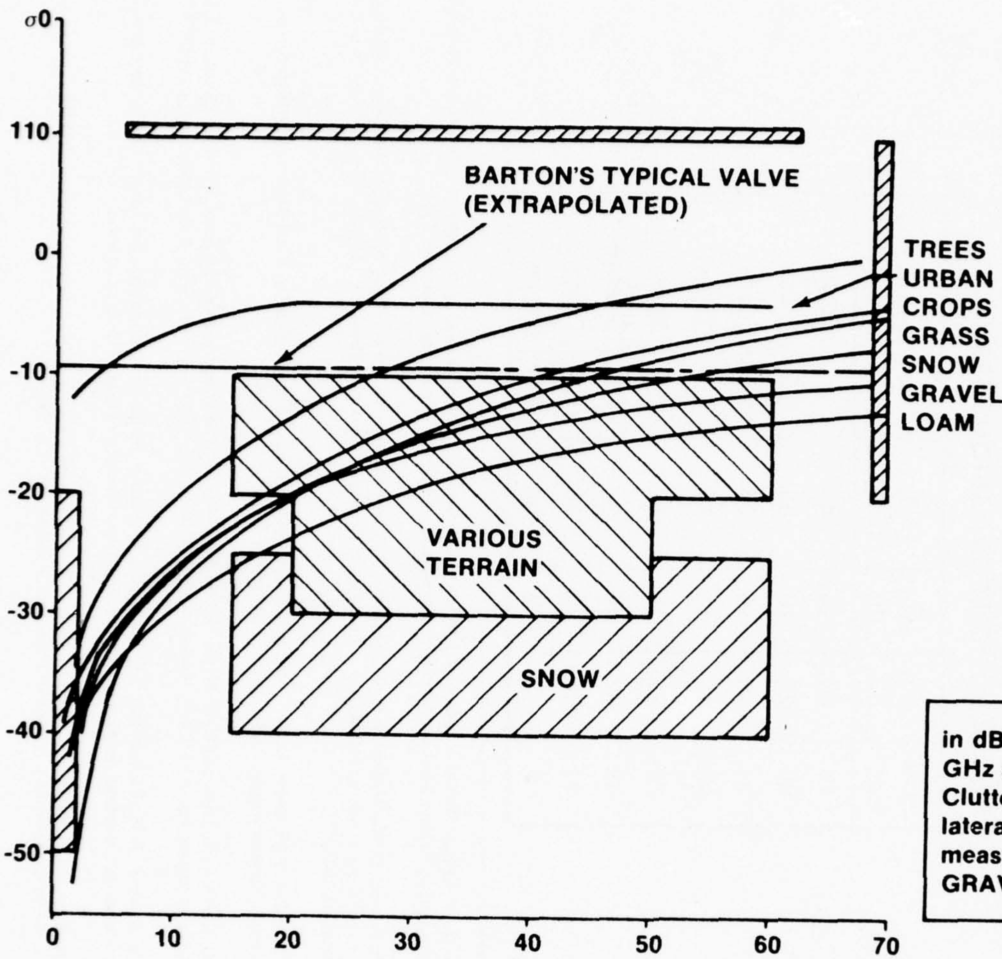
42. *Application of Millimeter Radars*, System Planning Corporation, Arlington, Virginia, Final Report on Defense Advanced Research Projects Agency Order 2353, 31 December 1973.

43. N.C. Currie, F.B. Dyer and R.D. Hayes, *Radar Land Clutter Measurements at Frequencies of 9.5, 16, 35, and 95 GHz*, Technical Report No. 3 EES/GIT Project A1485, Contract No. DAAA25-73-C-0256, Atlanta, Georgia, 2 April 1975.

44. J.M. Loomis, R.H. Farmer and T.D. Hodgens, *Millimeter Wave Beamrider Test*, US Army Missile Research and Development Command, Redstone Arsenal, Alabama, Technical Report T-78-27, September 1977.

45. H.E. Kins, C.J. Samites, D.E. Snow and R.I. Colliton, "Terrain Backscatter Measurement at 40 and 90 GHz," *Institute of Electrical and Electronics Engineers Transactions* AP-18, 1970, p. 780.

46. C.R. Grant, and B.S. Yaplee, "Backscattering from Water and Land at Centimeter and Millimeter Wavelengths," *Proc. IRE* 4T, 1957, p. 976.



in dB (m^2/m^2) at a frequency of 95 GHz as a function of grazing angle. Clutter model solid curves, cross lateral curve represents range of measured value movements. GRAVEL

Figure 2. Relative clutter cross section.

Barton recommends the use of the following values of σ_o when the exact nature of the terrain and the incidence angle is unknown: $\sigma_o = -26$dB at $\lambda = 3.2$ cm, $\sigma_o = -15$ dB at 8.6 mm.[1] From Equation (35) it is seen that the frequency dependence of σ_o is proportional to $C_3 \log (\lambda / \lambda_o)$. Using the average of all values of C_3, σ_o at 95 GHz is estimated to be

$$\sigma_o \cong -10 \text{ dB} \tag{36}$$

This value of σ_o is also indicated on *Figure 2*. As can be seen, it represents a worse case estimate for all terrain except gravel and moderate grazing angles.

In order to estimate the importance of clutter on a millimeter radar in a ground combat situation, a 95 GHz radar using a 10 cm diameter antenna with an antenna efficiency of 60%, a pulse width of 10 nseconds, and a range of 5 km should be considered. A relative clutter cross section of -20 dB, which is on the order of the largest measured value for grazing incidences and is 10 to 20 dB greater than the value predicted by Equation (35) will be assumed. With these assumptions a clutter cross section of 1.7 m^2 is obtained.

Typical tank targets have radar cross sections of < 1 m^2 to approximately 100 m^2 depending on aspect angle. A value of ≈ 20 m^2 is typical of most aspects and is frequently assumed for the purpose of analysis. Although the predicted clutter cross section will be on the order of the target cross section, in the worst case it will generally be at least an order of magnitude smaller. In estimating the clutter the maximum range, a pessimistic value of σ_o and a fairly wide beam divergence have been assumed. Minimum antenna size and lowest millimeter wave frequency were assumed. Increasing antenna size and/or frequency will decrease the beam diameter and, therefore, reduce the clutter. Therefore, in practical cases the clutter cross section will actually be less than the above value.

On the basis of the preceding analysis it appears that by the use of relatively narrow beams and reasonably short pulses, clutter can be reduced to a tolerable level so that special clutter rejection techniques will not be required.

TABLE 2. PARAMETERS USED IN COMPUTING CLUTTER CROSS SECTION.

Antenna Diameter	D	10 cm
Antenna Efficiency	η	60%
Frequency	f	95 GHz
Beam Width	$\theta\beta$	32.5 mrad
Depression Angle	δ	5% or less
Pulse Width	τ	10 nsec
Range	R	5 km
Clutter Area	Ac	172 m^2
Relative Clutter Cross Section	σ_O	-20 dB (m^2/m^2)
Clutter Cross Section	σ_S	1.7 m^2

7. TOTAL TRACKING ERROR

A. CONTRIBUTION OF ERROR SOURCES

If the angle fluctuations due to each individual tracking error are independent, gaussian random variables, then the mean square fluctuation in the tracking angle will be given by the sums of the individual mean square fluctuations that is,

$$\sigma^2_{TOTAL} = \sigma^2_N + \sigma^2_\lambda + \sigma^2_m + \sigma^2_s + \sigma^2_g + \sigma^2_c + \sigma^2_{sv} \qquad (37)$$

where the terms on the right hand side of Equation (37) are the mean square tracking errors due to receiver noise, propagation effects, multipath, target scintillation, glint, clutter, and servo noise, respectively. With the exception of servo noise each of these terms has been discussed in a previous section of this report.

It is instructive to examine the functional dependence of each of these terms on the various system parameters. The range dependence of each term is shown in *Figure 3*. As can be seen two terms, the receiver noise and the propagation noise increase with range. Receiver noise has the stronger dependence, increasing as the range squared in the absence of significant atmospheric attenuation. When there is appreciable attenuation, the thermal noise will increase much more rapidly than R^2 due to the presence of an exponential factor in the range equation. Two of the noise terms, glint and clutter, decrease with increasing range and the remaining terms are relatively range independent. The total tracking error will therefore be predominated by thermal noise at long ranges and by glint at short ranges. As can be seen from *Figure 3* there will be some intermediate range at which the total tracking error will be minimum. Thermal noise and clutter can be reduced by increasing the antenna size thereby reducing the beamwidth. Target noise will also probably be reduced due to aperture averaging by the receiving antenna.Thermal noise is inversely proportional to the pulse width for constant peak power. Clutter, on the other hand, increases linearly with pulse width due to an increase in clutter area. The other terms are independent of pulse width for the range of parameters of interest in clutter area. The other terms are independent of pulse width for the range of parameters of interest in this study.

Only the thermal noise term depends on transmitted power. Thus it is clear that increasing the radar power will increase the maximum range at which a given tracking accuracy can be obtained but will do nothing to improve the accuracy at short ranges where the error is due primarily to glint. It should be noted that if there is appreciable atmospheric attenuation present, the tracking error will increase rapidly with range once thermal noise becomes the predominant source of error. Since the dependence on range goes like $R^2 e^{\alpha R}$ and the dependence on peak power like $P^{-1/2}$, it requires a very large increase in power to obtain a small increase in maximum operating range.

The operating frequency enters into the thermal noise term in two ways. First, there is an explicit dependence on the inverse square of the frequency due to decreasing beamwidth obtained at higher frequency. Second, there is an implied frequency dependence through the frequency dependence of the atmospheric attenuation constant and, to a lesser degree, the system losses. Thus the choice of an operating frequency will be primarily a trade-off between narrow beamwidth at higher frequencies and better propagation at lower frequencies. This trade-off will be discussed in more detail in the following section. Availability of components will also influence the choice.

The other error terms are only weakly frequency dependent. The clutter cross section will vary a few dB over the millimeter wavelength range, and atmospheric turbulence effects may change slightly but this in general will not influence the choice of operating frequency.

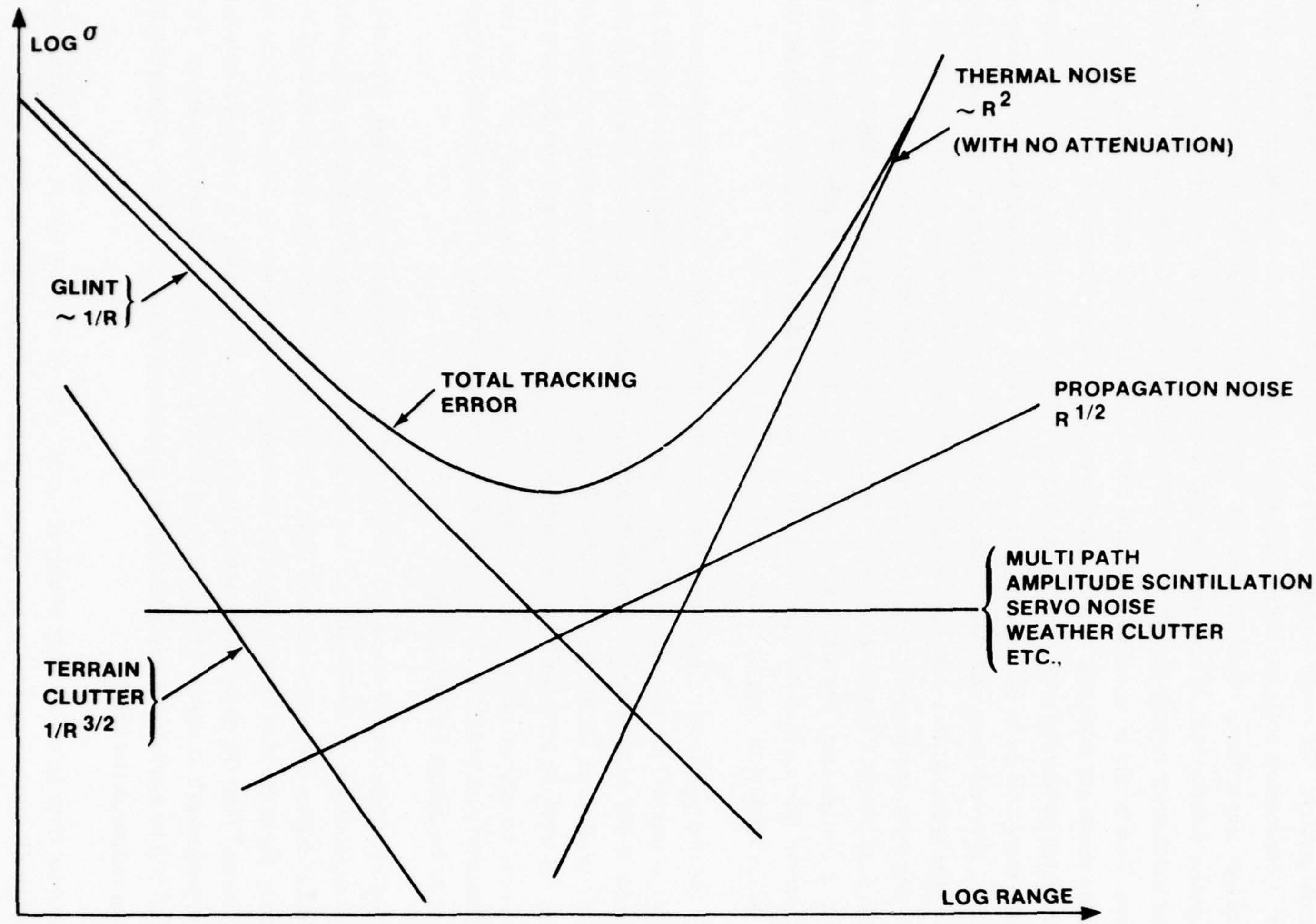


Figure 3. Dependence of various sources of tracking error on range (representative).

B. APPLICATION TO A MILLIMETER WAVE RADAR

As an example of the performance that can be expected with a millimeter wavelength tracking radar, the tracking accuracy versus range for a typical millimeter wavelength system has been plotted. The system parameters chosen are:

Operating Frequency	f	95 GHz
Antenna Diameter	D	0.5 m
Antenna Efficiency	η	60%
Peak Power	P_T	1 W
Target Cross Section	σ	$20 m^2$
Atmospheric Attenuation	α	0.5 dB/km
Background Temperature	T	273°K
Pulse Width	τ	50 nsec
IF Bandwidth	B	20 MHz
Receiver Noise Factor	N_F	8 dB
System Loss	L	13 dB
Error Slope	k_s	1.5
Pulse Repetition Frequency	f_R	20 KHz
Servo Bandwidth	β	2 Hz
Target Extent	L	2 m
Depression Angle	ϕ	0°

Earth Surface Roughness	σ_h	25 cm
Earth Surface Reflectivity	ρ	0.1
Scan Frequency	f_s	100 Hz
Glint Frequency	f_g	5 Hz

Figure 4 shows the tracking error that results from thermal (receiver) noise, angle noise (glint), target scintillation and multipath. It is clear that at low ranges glint will be the most important source of error and at long ranges receiver noise will predominate. The best tracking accuracy will be obtained at a range of about 4600 m. At this range the rms angle fluctuations can be expected to about 0.2 mrad.

The error calculations shown in *Figure 4* assume no reduction in glint. As previously stated, most millimeter wave sources have a natural frequency "chirp" and additional frequency agility could be incorporated to reduce glint. *Figure 4* therefore represents the worst possible case in so far as the glint error is concerned. *Figure 5* shows the total tracking error when frequency agility is used to reduce glint. Here N is the number of independent samples obtained during one measurement period. Value of N of 1 represents no frequency agility and $N = \infty$ corresponds to the case of the glint error having been completely eliminated. As shown in a previous section of this report, $N \simeq 5$ in a reasonable value for millimeter radars. In *Figure 5* it has been assumed that the range independent errors (scintillation, multipath, servo noise) contribute a total of 0.05 mrad to the total tracking error.

Figure 6 shows the effect of increased atmospheric attenuation on the system tracking performance for both a frequency agile (N = 100) and a non-agile system. The atmospheric tracking error is plotted for the ideal case (0 dB/km) and for attenuations of 2 and 4 dB/km. These were chosen to represent adverse weather conditions such as 4 mm/hr rain very heavy (visibility less than 20 m) fog.

The previous figures have assumed a target extent of 2m and have included multipath. They are therefore representative of the elevation errors in tracking a tank or similar target. To calculate azimuth errors, for a side aspect, the extent should be about 6m and multipath should be omitted. Typical azimuthal tracking errors are shown in *Figure 7*. It is interesting to n while the minimum tracking error was increased by a factor of two, the range at which this minimum occurs was extended from 4600m to 7000m.

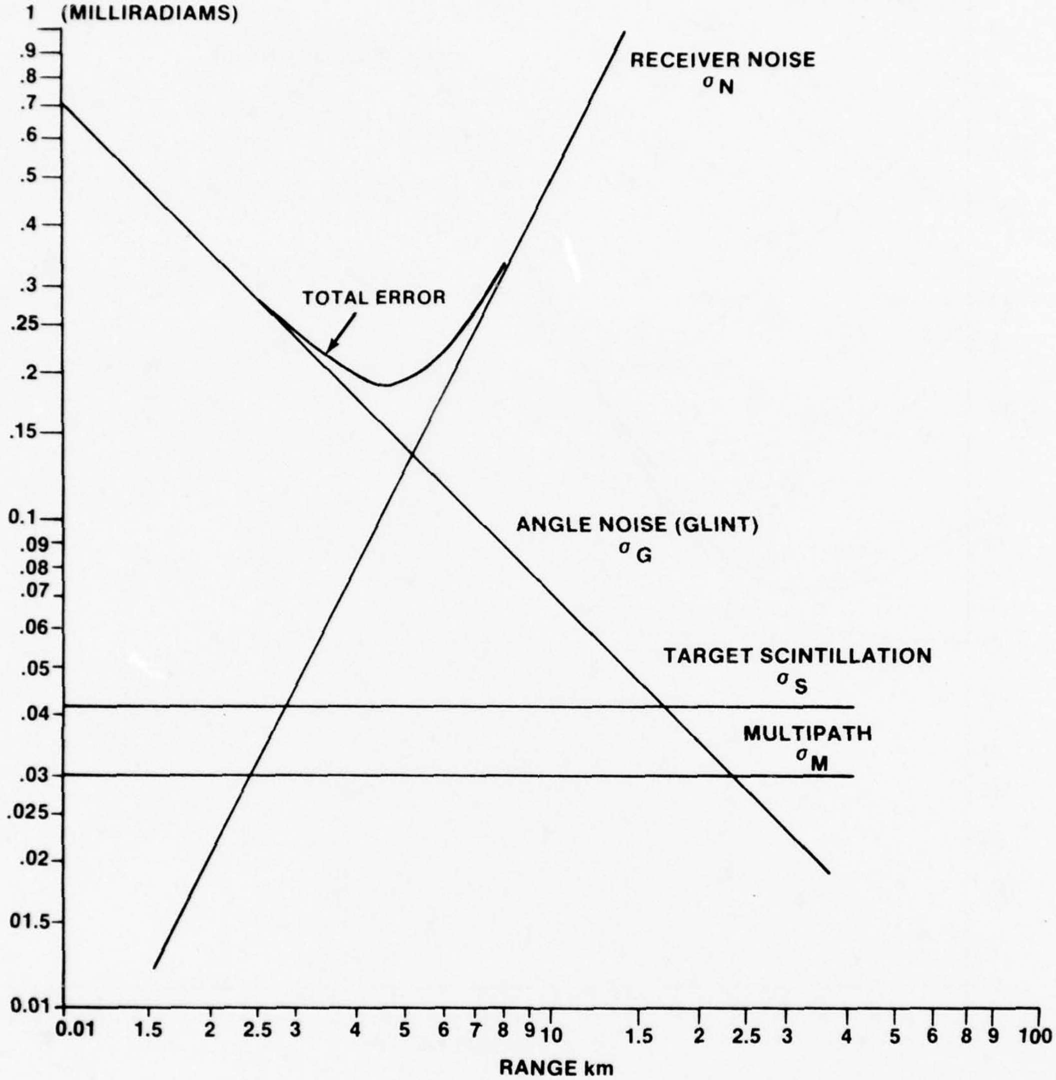


Figure 4. Receiver Noise, Angle Noise (Glint), Target Scintillation and multipath error as a function of range for a typical millimeter wavelength tracking radar (Elevation Angle).

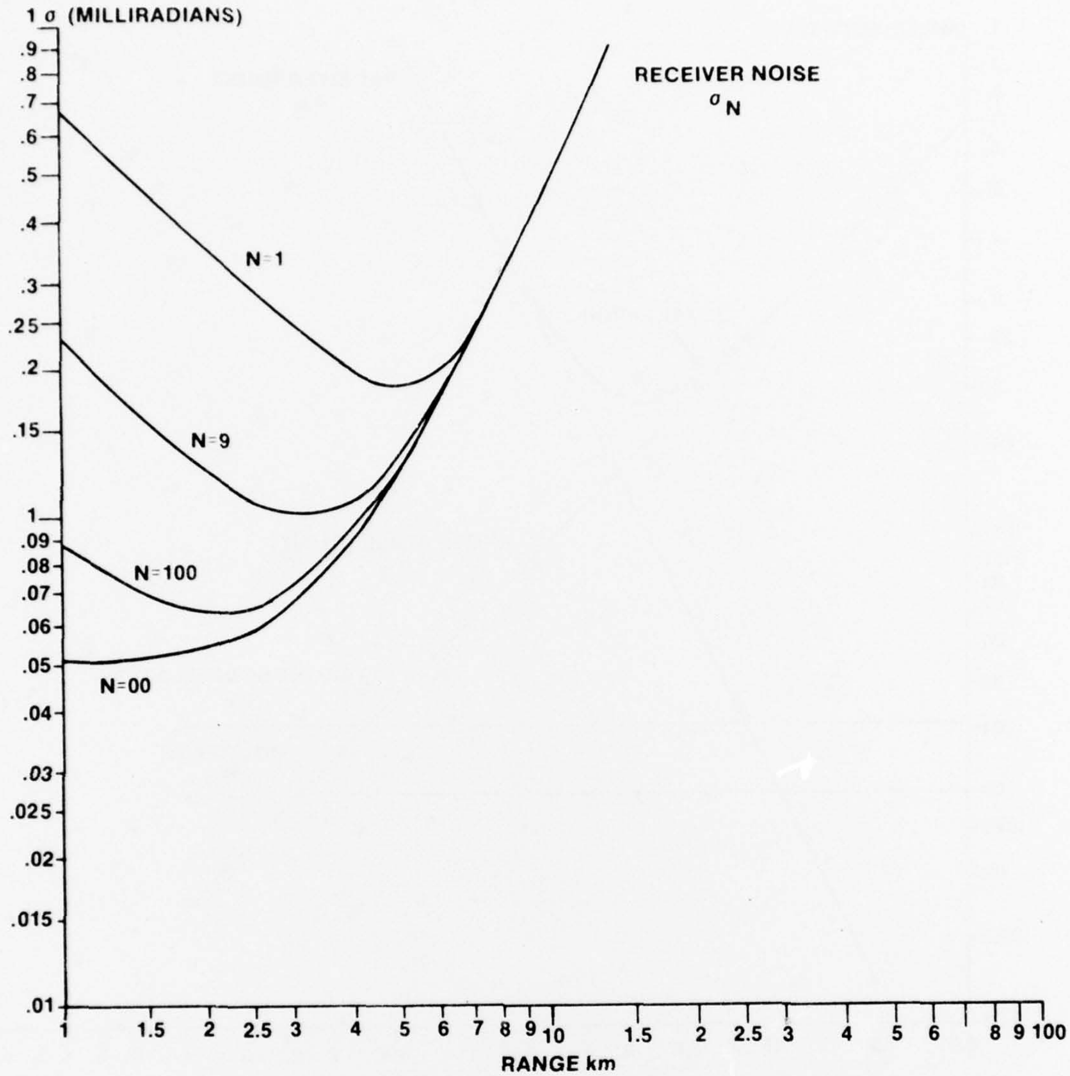


Figure 5. Effects of frequency agility on tracking accuracy.

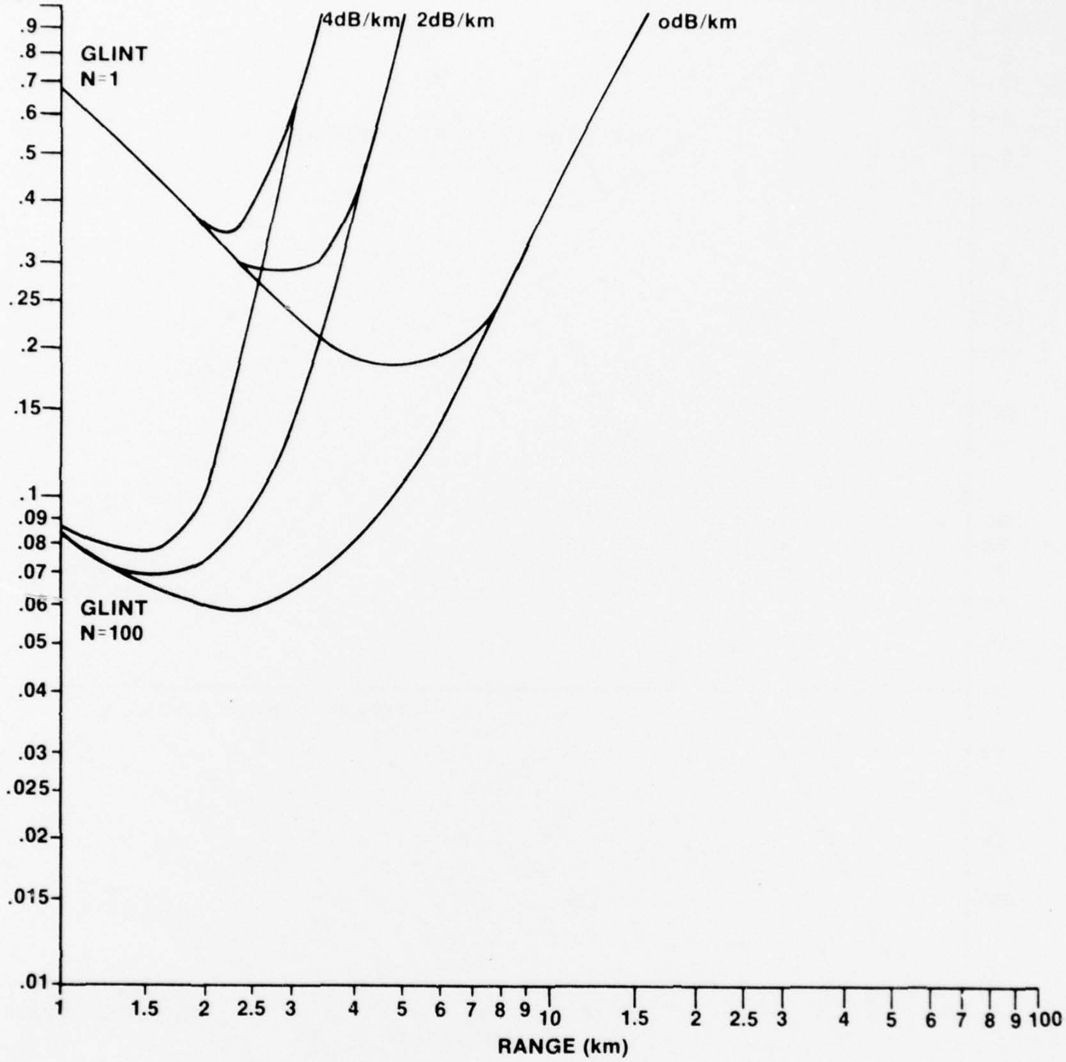


Figure 6. Effects of atmospheric attenuation on track accuracy of both fixed frequency and frequency agile radars.

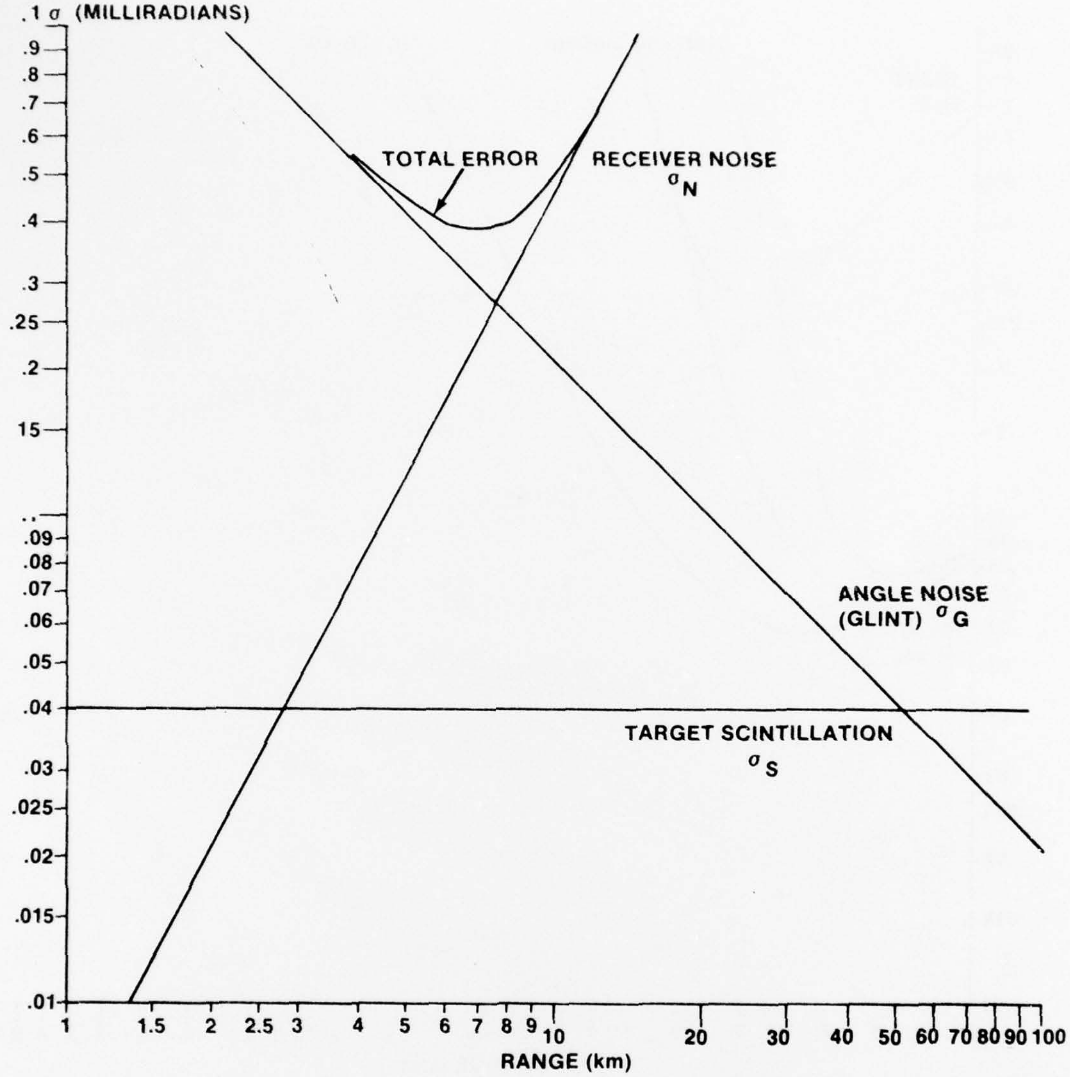


Figure 7. Azimuthal tracking error as a function range due to glint, receiver noise and range independent sources.

8. SELECTION OF OPERATING FREQUENCY

As mentioned in the previous section, choice of operating frequency is largely a trade-off between better propagation at lower frequencies and the improved tracking accuracy obtainable at higher frequencies because of the narrower beamwidths. To investigate the dependence of tracking performance on frequency, the peak transmitter power required for precision tracking has been computed for ranges of 3, 4, and 5 km in each of the atmospheric windows from 35 GHz to 462 GHz. For comparison, the power required at 10 GHz was also computed. For the purpose of these calculations, it was assumed that the tracking error was due to the combination of glint and thermal noise. It was further assumed that the radar would be frequency agile with a diversity sufficient to yield nine independent samples of the glint spectra for each measurement of angle. A range independent error of 0.05 mrad was included to allow for servo noise, target amplitude noise and multipath effects. The required tracking error was taken to be that rms angular deviation corresponding to a 1m diameter circle at the target; i.e.,

$$\sigma = \frac{0.5}{R} \tag{38}$$

The tracking error equation can then be expressed, as

$$\sigma^2 = \sigma_g^2 + \sigma_N^2 + (0.05 \times 10^{-3})^2 \tag{39}$$

hence

$$\left(\frac{0.5}{R}\right)^2 = \left(\frac{0.35\ L}{\sqrt{N}\ R}\right)^2 + \sigma_N^2 + (5 \times 10^{-5})^2 \tag{40}$$

After substituting the appropriate expression for σ_N Equation (40) may be solved for the transmitter power needed to give the specified tracking accuracy. Taking the transmitter antenna to be 1m in diameter and all other parameters the same as those used in section 7, we obtain

$$P_T = \frac{2.72 \times 10^{19}\ R^6\ e^{2\alpha R}}{f^4\ (0.196 - 2.5 \times 10^{-9} R^2)} \tag{41}$$

Table 3 shows the power computed from (41) for ranges of 3, 4 and 5 km and frequencies of 10, 35, 94, 140, 222, 345, 414 and 462 GHz. Also shown in *Table 3* are the assumed values of attenuation for each atmospheric window. These values are representative of a moderate rain (4mm/hr at 15°C) or heavy fog.

TABLE 3. PEAK POWER REQUIRED FOR PRECISION TRACKING IN ADVERSE WEATHER

Frequency GHz	Attenuation dB/km	Peak Power (Watts)		
		R - 3 km	R - 4 km	R - 5 km
10	0.0	11.4	71	319
35	1.4	0.527	6.2	52.9
95	3.9	0.321	11.5	313
140	4.8	0.225	12.9	510
222	7.0	0.744	121	13×10^{3}
345	19.0	2×10^{6}	8×10^{10}	3×10^{18}
414	28.0	2.5×10^{11}	6×10^{17}	1×10^{25}
462	65.0	2.5×10^{33}	2×10^{49}	7×10^{57}

The required transmitter power, expressed in dBw, is shown in *Figure 8*.Although the computed points are connected, it is not intented to imply that it is possible to interpolate between them. On the contrary, they are outside the windows the attenuation, and, therefore, the required power will be very large.

From *Figure 8* it is seen that at either 35, 94 or 140 GHz the required transmitter power will be minimum. At which frequency the minimum falls will depend upon the range. Above 220 GHz the power requirements increase rapidly. Clearly, the 35-140 GHz region appears to be most likely to allow precision tracking at moderate ranges. Although the required power at

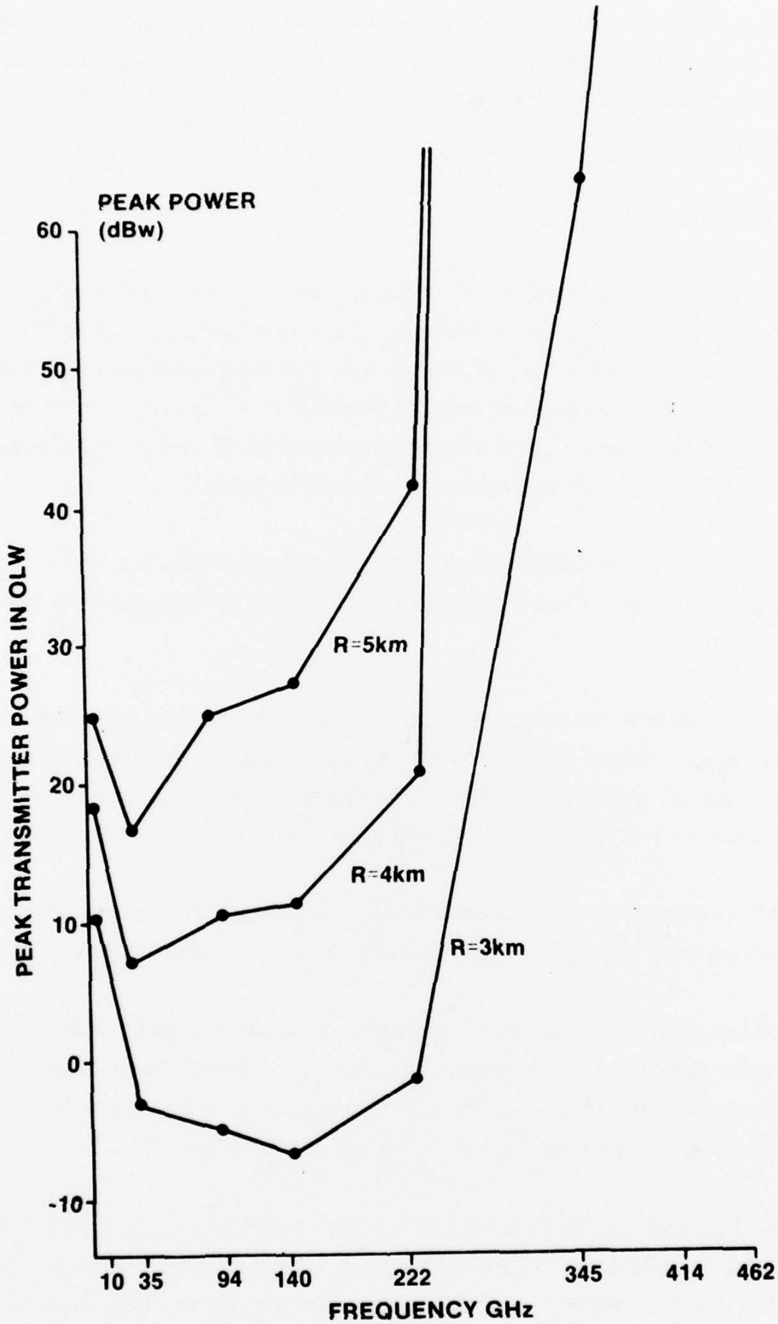


Figure 8. Peak power requirement for precision tracking in adverse weather as a function of frequency.

220 GHz is somewhat greater than at lower frequencies, this window cannot be rejected on the basis of this analysis. It should be remembered, however, that for a given type oscillator the maximum available output power decreases with increasing frequency and receiver noise factors tend to be worse at high frequencies. These factors will tend to favor the operation at lower frequencies.

9. CONCLUSIONS

A number of sources of error affect the tracking performance of millimeter radars. These include receiver noise, target noise, multipath, clutter and propagation errors. As long as reasonable antenna sizes, a few tens of centimeters, and reasonable power, a few watts, are available, the contribution of receiver noise to the total tracking error can be reduced to an insignificant level at least under good propagation conditions. Under degraded propagation conditions, e.g., heavy rain the receiver noise may predominate.

With the exception of atmospheric attenuation, propagation effects such as turbulence and refraction are unimportant at these frequencies and in the geometries typically encountered in land combat situations.

It appears from available data that by using the narrow beams and short pulses available in the millimeter region, clutter can be reduced to an acceptable level so that special clutter rejection techniques will not be required. The possible exception might be a target concealed in trees. In this situation the clutter would fill the beam and would be unresolvable in range.

A reasonable amount of terrain backscatter data is available. However, because of the wide diversity of terrain that must be considered, additional data would always be useful.

Target noise is a significant source of tracking error. Glint models of military targets in the millimeter regime appear to be inadequate to accurately assess the magnitude of the glint errors. The theoretical treatment of glint used in many analyses is oversimplified. Additional work, both theoretical and experimental, is needed in this area.

Much of the theory of multipath error that has been developed for conventional radar may not be applicable to millimeter radars operating in a land combat situation. There are two reasons for this: (1) The surface roughness is many times larger than the wavelength, and (2) the geometries are much more extreme than those normally considered in "low-angle tracking" situations. Existing theory indicates that multipath is a severe problem. The little

experimental data that is available seems to show that multipath effects are not as large as expected. Clearly, more work is needed in this area, especially in developing a theoretical description of the multipath phenomenon. An adequate theory of multipath at millimeter wavelengths should consider both specular and diffuse components of reflection and should include the effect of glint since glint and multipath effects are interrelated. Static multipath measurements should be made over a wide range of angles and terrains.

Various techniques are available for reducing multipath. These include frequency diversity, complex angle tracking, maximum likelihood estimation, off axis tracking, polarization diversity, etc. In general, these techniques appear to be either ineffective in the environment being considered, or else too complex to implement in a missile guidance system.

REFERENCES

1. D.K., *Radar System Analysis,* Artech House, Dedham, Massachusetts, 1976, p. 279.

2. Guenther, B.D. and Carruth, R.T., *Millimeter Wave Sources for Radar Applications,* US Army Missile Research and Development Command, Redstone Arsenal, Alabama, Technical Report.

3. Waldman, J., *Millimeter and Submillimeter Wave Receivers,* US Army Missile Research and Development Command, Redstone Arsenal, Alabama, Technical Report TE-77-17, 15 July 1977.

4. Gamble, W.L. and Hodgens, T.D., *Propagation of Millimeter and Submillimeter Waves,* US Army Missile Research and Development Command, Redstone Arsenal, Alabama, Technical Report TE-77-14, 22 June 1977.

5. Richer, D.A., Bauerle, D.G. and Know, J.E., *94 GHz Radar Cross-Sections of Vehicles,* Ballistics Research Laboratory Memorandum Report No. 2491, Aberdeen Proving Ground, Maryland, June 1975.

6. *Radar Millimeter Wave Backscatter Measurements and Hard Targets,* Experiment Station, Georgia, Institute of Technology, Atlanta, Georgia, July 1976.

7. Muchmore, R.B. and Whellon, A.D., "Line of Sight Propagation Phenomena II Ray Treatment," *Proceedings IRE* 43, 1955, pp. 1437-49.

8. Whellon, A.D., "Near Field Correction to Line of Sight Propagation," *Proceedings IRE* Vol. 43, 1955, pp. 1459-1466.

9. Fante, Ronald L., "Electromagnetic Beam Propagation in Turbulent Medic," *Proceedings of the Institute of Electrical and Electronics Engineers,* Vol. 62, 1974, pp. 1669-1692.

10. Barton, David K., "Low Angle Tracking," *Proceedings of the Institute of Electrical and Electronics Engineers*, Vol. 62, 1974, pp. 687-704.

11. Beckmann, P. and Spizzichino, A., *The Scattering of EM Waves from Rough Surfaces*, Pergamon Press, New York, New York, 1963.

12. Barton, David K., ed., *Radars, Volume 4, Radar Resolution and Multipaths*, Arthtech House, Dedham, Massachusetts, 1975.

13. Dees, Julian W., and Schuchardt, James M., *Effects of Multipath on Millimeter Beamrider Systems*, US Army Missile Research and Development Command, Redstone Arsenal, Alabama, February 1978.

14. Richard, Victor W., *Low Angle Tracking at Millimeter Wavelengths*, US Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland.

15. General Research Corporation, *Proceedings of Defense Advanced Research Projects Agency Low Angle Tracking Symposium*, Santa Barbara, California, January 1977.

16. Dunlap, Samuel O., *Selected Topics on Radar Multipath*, US Army Missile Research and Development Command, Redstone Arsenal, Alabama, Technical Report TR-CR-77-7, August 1977.

17. Shackleford, R.G. and J.J., Gallagher, *Millimeter Wave Beamrider*, US Army OM, Redstone Arsenal, Alabama, Technical Report TR-CR-77-7, August 1977.

18. Thompson, F.H. and Kittredge, F.A., *A Study of the Feasibility of Using 35 GHz and 94 GHz as a Means of Improved Low Angle Tracking*, National Research Laboratory Report 2249, May 1971, Advanced Development 72108.

19. Private Communication

20. Victor, Richard V., *Millimeter Wave Radar Application to Weapon System*, US Army Ballistic Research Laboratory Memorandum Report No. 2631, Aberdeen, Maryland, June 1976.

21. Richer, K.A., *4.4 MM Wavelength Near Earth Propagation Measurements* (U), Ballistic Research Laboratories Memorandum Report No. 1403, May 1962, (Confidential) Advanced Development 331098.

22. Wilson, C.L., *Antenna Pointing Errors in Simultaneous Lobing Antenna System,* Ballistic Research Laboratories Technical Note No. 1453, Advanced Development 608997, June 1962.

23. Wilson, C.L., *Antenna Pointing Errors in Sequential Lobing Antenna System,* Ballistic Research Laboratories Technical Note No. 1463, Advanced Development 609009, May 1962.

24. O'Dell, T.W., *Final Report for Missile Guidance Subsystem Feasibility Program-Phase 1A* (U), General Precision Laboratories Report No. P026 (Confidential).

25. O'Dell, T.W., *Final Report for Missile Guidance Subsystem Feasibility Program-Phase 2* (U), General Precision Laboratories Report No. 14990, June 1962 (Confiential).

26. Leggett, N., *Final Report, Breadboard Feasibility Study of the Derring Weapon Guidance System,* Bendix Pacific Division Report No. 91-139-1 (U), May 1963.

27. Kammerer, J.E. and Richer, K.A., *4.4 MM Near Earth Antenna Multipath Pointing Errors* (U), Ballistic Research Laboratories Memorandum Report No. 1559, Advanced Development, 443211, March 1964 (Confidential).

28. Kammerer, J.E. and Richer, K.A., *4.4 MM Wavelength Precision Antennas and Mount,* Ballistic Research Laboratories Memorandum Report No. 2576, Advanced Development 449726, July 1964.

29. Kammerer, J.E. and Richer, K.A., *140 GHz Millimetric Bistatic Continuous Wave Measurements Radar,* Ballistic Research Laboratories Memorandum Report No. 2730, Advanced Development 484693, January 1966.

30. Kammerer, J.E., and Richer, K.A., *Pointing Errors of a 140 GHz Bistatic Radar System Illuminating US Army Targets* (U), Ballistic Research Laboratories Memorandum Report No. 1755, Advanced Development 375942, June 1972.

31. Private Communication.

32. Bockmiller, W.H., and Dax, P.R., *Radar Low Angle Tracking Study*, National Aeronautics and Space Administration Contract Report No. 1387, Westinghouse Electric Corporation, Baltimore, Maryland, June 1969.

33. Root, Lloyd W., and Cullis, R.N., *Multipath Environment Active RF Seeker (MARFS)*, US Army Missile Command Report.

34. McGee, R., *Multipath Suppression by Swept Frequency Methods*, Ballistic Research Laboratories Memorandum Report No. 1950, Advanced Development 682728, November 1968.

35. Delano, Richard H., "A Theory of Target Glint or Angular Scintillation in Radar Tracking," *Proceedings IRE.*, Vol. 41, 1953, p. 1778.

36. Straiton, A.W., *Radar Target Modeling at 94, 140, and 220 GHz*, Final Report on Contract DAAG29-76-D-0100, US Army Missile Research and Development Command, Redstone Arsenal, Alabama, January 1978.

37. Barton, David K., ed., *Radars, Vol. 6: Frequency Agility and Diversity*, Artech House, Dedham, Massachusetts, 1977.

38. Howard, Ray, "Improving Radar Range and Angle Detection with Frequency Agility," *Microwave Journal*, May 1966, p. 63.

39. Lind, Goran, "Reduction of Radar Tracking Errors with Frequency Agility," *Institute of Electrical and Electronics Engineers Transactions Aerospace and Electronic System* AES-4, 1967, p.10.

40. Green, George M.; Shaw, Wesley H.; and Stewart, James P.; *Target Background Measurements Using Pulse Millimeter Wave Seeker*, Martin Marietta Aerospace Corporation, Orlando, Florida, 19 November 1975.

REFERENCES (Concluded)

41. Roeder, R.S., et. al., *Millimeter Wave Semiactive Guidance System Concept Investigation,* Sperry Microwave Electronics Division Report No. SJ242-847A-5, Final Report. Defense Advanced Research Projects Agency Order No. 3146, November 1978.

42. *Application of Millimeter Radars,* System Planning Corporation, Arlington, Virginia, Final Report on Defense Advanced Research Projects Agency Order 2353, 31 December 1973.

43. Currie, N.C.; Dyer, F.B.; and Hayes, R.D.; *Radar Land Clutter Measurements at Frequencies of 9.5, 16, 35, and 95 GHz,* Technical Report No. 3, EES/GIT Project A1485 Contract No. DAAA25-73-C-0256, Atlanta, Georgia, 2 April 1975.

44. Loomis, J.M.; Farmer, R.H.; and Hodgens, T.D., *Millimeter Wave Beamrider Test,* US Army Missile Research and Development Command, Redstone Arsenal, Alabama, September 1977.

45. Kins, H.E.; Samites, C.J.; Snow, D.E.; and Colliton, R.I., "Terrain Backscatter Measurement at 40 and 90 GHz," *Institute of Electrical and Electronics Engineers Transactions,* AP-18 1970, p. 780.

46. Grant, C.R. and Yaplee, B.S., "Backscattering from Water and Land at Centimeter and Millimeter Wavelengths," *Proceedings IRE,* 4T (1957), p. 976.

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